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Spectral Characteristics of Soils Related to the Interaction of Soil Moisture, Organic Carbon, and Clay Content

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SPECTRAL CHARACTERISTICS OF SOILS RELATED TO THE INTERACTION OF SOIL MOISTURE, ORGANIC CARBON, AND CLAY CONTENT

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of

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ABSTRACT

Beck, Robert H. M.S., Purdue University, May, 1975. Spectral characteristics of soils related to the interaction of soil moisture, organic carbon, and clay content. Major Professor: Dr. W. W. McFee.

By measuring certain physical properties of fifteen soils typical of Wisconsin-aged, glacial till soils capped with less than 60 inches of loess in Indiana, the variations in spectral response in the laboratory were explained. Spectral reflectance measured with the Exotech 20-C can be significantly explained by percent moisture, organic carbon, and clay content of these soils. The soils studied were predominantly silty with a range of organic carbon from .60 to 1.33%. The moisture content of the soils was controlled by use of the pressure membrane at 15 bars, pressure plates at 1/3 bar, and oven dried at 105°C for 24 hours in a forced air dryer. The moisture of the samples was equilibrated, and then illuminated artificially by a General Electric DXW lamp and spectrally measured from .53 μm to 2.32 μm with Exotech 20-C.

The interpretation of the results allows me to suggest three wavelength band widths for use in the field when attempting to classify surface soils and increase the accuracy in mapping them by multispectral scanner techniques.

1. To map organic carbon use the band from .90 to 1.22 μm.
2. To map water content use the band from 1.50 to 1.73 μm.
3. To map clay use the band from 1.50 to 1.73 μm.

The amount of moisture present affects the spectral response of soils the most followed by organic carbon content, percent silt and then percent clay with multiple regression analysis.

INTRODUCTION

Organic carbon content of soils is the physical property of soils recognized by most researchers to be most important in affecting the spectral response of soils (Shields et al., 1968; Bowers and Hanks, 1965; Baumgardner et al., 1970; Page, 1974; Horvath, Montgomery and Van Zile, 1971; Al-Abbas, Swain, and Baumgardner, 1972). Some laboratory instruments that have been used to measure different portions of the electromagnetic spectrum reflected by soils (Fig. 1) are the Bausch and Lomb Spectronic 20 measuring in the ultraviolet region (Shields et al., 1968), the Hunterlab model D25D2M in the visible portion of the spectrum (Page, 1974), and the Beckman DK2A and DU spectrophotometer in the visible and near infrared (Bowers and Hanks, 1965). Outdoors, the Michigan aircraft scanner[1] has been used extensively to measure reflected energy in the visible and near infrared regions (Baumgardner et al., 1970; Horvath et al., 1971; Al-Abbas et al., 1972). Other soil properties have been considered, but no study included controlled soil moisture, organic carbon, sand, silt and clay in the analysis of spectral data. Many of the studies used the spectral data to estimate the individual soil properties but none, except Bowers and Hanks, attempted to evaluate how soil properties affect the spectral response. I felt the accuracy of estimating soil properties from the reflected spectral energy

[1] From the Environmental Research Institute of Michigan, Ann Arbor, Mich.

Fig. 1 - A portion of the Electromagnetic Spectrum (from Hoffer and Johannsen, 1969).

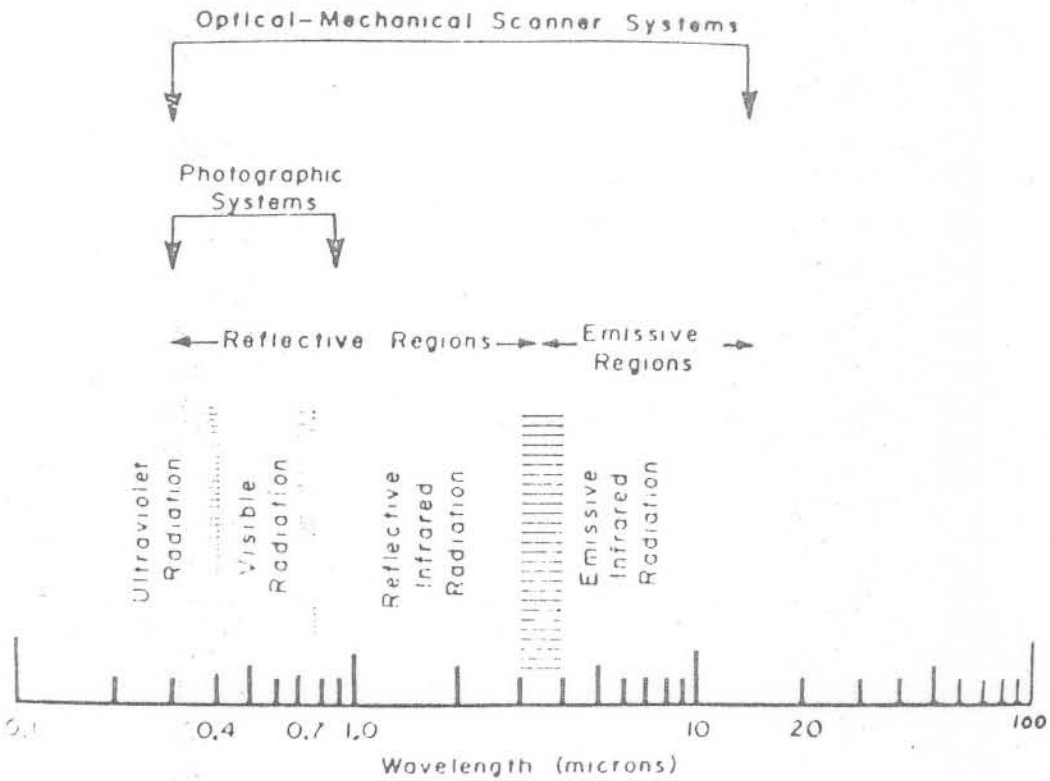

Optical-Mechanical Scanner Systems
Photographic Systems
Reflective Regions
Emissive Regions
Ultraviolet Radiation
Visible Radiation
Reflective Infrared Radiation
Emissive Infrared Radiation
0.4
0.7
1.0
10
20
100
Wavelength (microns)

Fig. 1

could be increased using methods proposed by others (Baumgardner et al., 1970; Horvath et al., 1971; Al-Abbas et al., 1972; West, 1972) if they used the spectral reflectance data from the wavelength regions that are affected by the soil property being estimated.

This approach was also taken by Montgomery (Montgomery and Baumgardner, 1974) but he attempted to utilize soil property data gathered by SCS-USDA soil characterization laboratories. His spectral data was collected using the Exotech-20-C indoors to measure 71 soils from 26 states. He attempted to establish characteristic spectral reflectance curves from .5-2.6 μm for each of the 10 soil orders as described in Soil Taxonomy and identified silt and the cation exchange capacity as the most important properties used to estimate variations in spectral response by multiple regression. His methods were similar to Condit's (1970) who measured 160 soils from 36 states (from .32-1.0 μm) and classified soils by their spectral curve into 3 typical or characteristic types.

My study followed Montgomery's approach but the surface soils were chosen from the Western part of Tippecanoe County, Indiana, which varied predominantly in organic carbon values. These soils developed in loess over Wisconsin-age, glacial till and the textures did not vary greatly. Spectral measurements between .53-2.32 μm were taken of the surface soils after they had been equilibrated at three moisture contents: oven dry, 15 BAR and 1/3 BAR. An Exotech 20-C with artificial illumination provided by a General Electric DXW lamp was used to make the spectral measurements of the soils in the laboratory. The organic carbon content was determined

by three methods to study the interpretation of the spectral data using the organic carbon values from the different methods (Appendix A). Then a stepwise, forward selection, multiple regression analysis (STEPR) was performed to help determine how much of the variation in spectral response at several wavelength bands (dependent variables) could be explained by the soil properties measured (independent variables).

LITERATURE REVIEW

"To study satisfactorily any heterogeneous group in nature, some sort of classification is necessary. This is especially true of soils. The value of experimental work of any kind is seriously restricted and may even be misleading unless the relation of one soil to another is known" (Brady, 1974). It is with this idea in mind the study of soils, or more specifically to classify soils, that leads to the use of remote sensing as a tool. Most research in soil classification has been conducted by individuals traversing the landscape, probing and observing the soils found there and then analyzing samples taken to the laboratory. For over 40 years the soil surveyor has found remotely sensed data (aerial photographs) to be quite useful in mapping soils. A suitable definition of remote sensing is found in D. M. Carroll's (1973a) review article on remote sensing techniques and their application to soil science. The definition of remote sensing from that article originally quoted Parker and Wolf: "The acquisition of information about an object (or phenomenon) which is not in intimate contact with the information gathering device is called remote sensing."

Black and white film sensitive to the visible portion of the electromagnetic spectrum (.38-.78 μm) was the first remote sensing data recorder. Then color film covering the same region of the spectrum was used but offered the photointerpreter more information

since the photo, like the landscape, is usually seen in color by the interpreter. With combinations of filters and special films, the state of the art of photographic remote sensors has developed to the point that we can measure the reflected solar radiation between .3-.9 μm. Several systems of multispectral photography have been developed which separate the visible (.38-.78 μm) and near infrared (.78-.9 μm) portions of the spectrum (Fig. 1) into several bands. These bands can be analyzed separately or overlayed in several combinations to enhance certain spectral characteristics being studied.

Since about 1965, instruments have been utilized which scan photographs or negatives for differences in optical density, and these densities are digitized and used in automatic data analysis by computers. An example conducted by Anuta et al. (1971) used digitized, multispectral, satellite photography from the Apollo 9 mission to attempt to map soils, crops, and geologic features. Using black and white photographs with appropriate filters, they digitized the film density of four bands in the visible region; .47-.89, .47-.61, .68-.89 and .59-.71 μm. Using a combination of three bands they were able to construct a soils map of the El Centro area in Imperial Valley, California, which approximated the general soil survey map. They concluded that three band, spectral data gathered at satellite altitude shows great promise for large-scale soil mapping.

With all this work in photographic remote sensing there are some disadvantages which have led to the development of new sensing

devices. Photographic sensors only cover the visible and near infrared portion of the electromagnetic spectrum. Much additional information is available from the infrared portions of spectrum beyond that recorded by photographic sensors (Fig. 1) since solar energy is still being reflected (.9-2.5 μm) and there is emissive radiation in the thermal infrared region.

It is this region (.52-2.32μm) of the spectrum that was used in my study. A review of the literature on photographic sensors by D. M. Carroll (1973a) concludes "it would seem that the well proven techniques of photographic interpretation will continue to be an important aid to the soil scientist, but the newer sensors may prove of equal value if they are carefully developed. These sensors are complimentary to, rather than competing with, conventional photographic sensors."

The non-photographic sensors are discussed in another review by Carroll (1973b). These sensors record the data in a form other than photographic film, frequently magnetic tape. The storage of data on magnetic tape lends itself to automatic data processing with computers. He discusses several types of sensors, but my main interest is the optical mechanical scanner which consists of a multiband spectrometer with a motor-driven mirror used to scan across the field of view. All the energy from a given scene passes through the same optical aperture, is dispersed according to its position in the spectrum, and is measured by sensitive detectors, whose output is recorded on magnetic tape. These multi-

spectral sensors scan discrete bands, selected at wavelengths that allow collection of data in a portion of the electromagnetic spectrum where the atmosphere does not absorb solar radiation. The visible and near infrared region from .3-2.5μ has been used frequently in remote sensing, since almost all the solar energy received at the earth's surface (Fig. 2) is contained within that range (Gates, 1965). Usually comparisons have been made between the quality of information gathered by non-photographic (optical mechanical) sensors and photographic sensors in the region of the electromagnetic spectrum common to both. Most of the interpretations made with non-photographic sensors have resulted from observations made from photographs of the same scene made at the same time.

Upon wetting, a dry soil appears darker. This phenomenon has been the primary subject of investigation using remote sensing. Angstrom, reported by Planet (1970), concluded that the decrease in reflectance of soils was due to the total internal reflections in the water film of the energy reflected from the soil surface itself. Planet's work (1970) supports Angstrom's conclusion that the darkening of soil upon wetting is due to optical effects of a thin layer of liquid on the surface of the soil.

With this in mind, work was conducted in 1965 (Bowers and Hanks, 1965) using a Beckman DK-2A spectrophotometer (.185-2.500 μm) and a Beckman DU spectrophotometer (.21-1.00μm). Three soils were studied to evaluate the influences of moisture content, organic matter and particle size on the reflected spectra. They noticed that as

Fig. 2 - A comparison between solar radiation at sea level and the General Electric DXW lamp (from DeWitt and Robinson, unpublished).

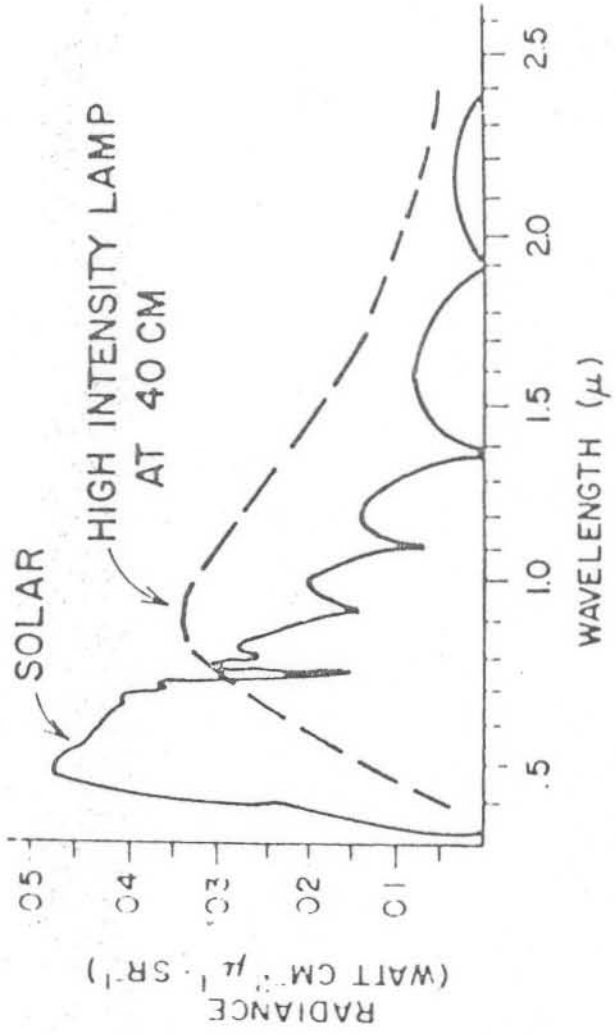

SOLAR
HIGH INTENSITY LAMP
AT 40 CM
.5
1.0
1.5
2.0
2.5
WAVELENGTH (μ)
.05
.04
.03
.02
.01
RADIANCE
(WATT CM⁻² μ⁻¹ · SR⁻¹)

Fig. 2

moisture increased the percent reflectance of the energy at all wavelengths decreased and that the curves of percent reflectance versus wavelength had similar shapes at all moisture levels. For the Newtonia silt loam (Fig. 3), they noticed two distinct absorption bands located at 1.4 and 1.9 μm which are wavelengths where solar radiation is strongly absorbed by water and specifically represent overtones of the fundamental frequencies (2.66, 2.73 and 6.269 μm) at which water molecules vibrate.

In a more recent study by Hunt and Salisbury (1970) the same findings were confirmed. They studied montmorillonite and kaolinite clays with a Cary Model 14 spectrophotometer covering the spectrum from .3-2.5 μm and found the spec ral reflectance curve of montmorillonite (Fig. 4) to look like that of Newtonia silt loam used in Bowers and Hanks study. The montmorillonite spectral reflectance curve is dominated by very strong absorption bands at 1.4 and 1.9μ m due to bound water typical of montmorillonite and usually a weaker absorption band at 1.16 μm possibly due to absorbed water (Lindberg and Snyder, 1972).

Kaolinite's major spectral reflectance features (Fig. 5) are several very strong hydroxyl bands in the near infrared centered near 1.4 and 2.2μ m. Lack of appreciable bound water is typical of kaolinite and is indicated by the weakness of the band at 1.9 μm. Their (Lindberg and Snyder, 1972) explanation of the absorption bands states that no bands due to the fundamental vibration modes occur in the range short of 2.5 μm, so that all features observed in the spectral curve are to be considered exclusively overtones or combination tones of fundamental

Fig. 3 - Percent reflectance vs. wavelength of incident radiation for the Newtonia silt loam at various moisture contents (from Bowers and Hanks, 1965).

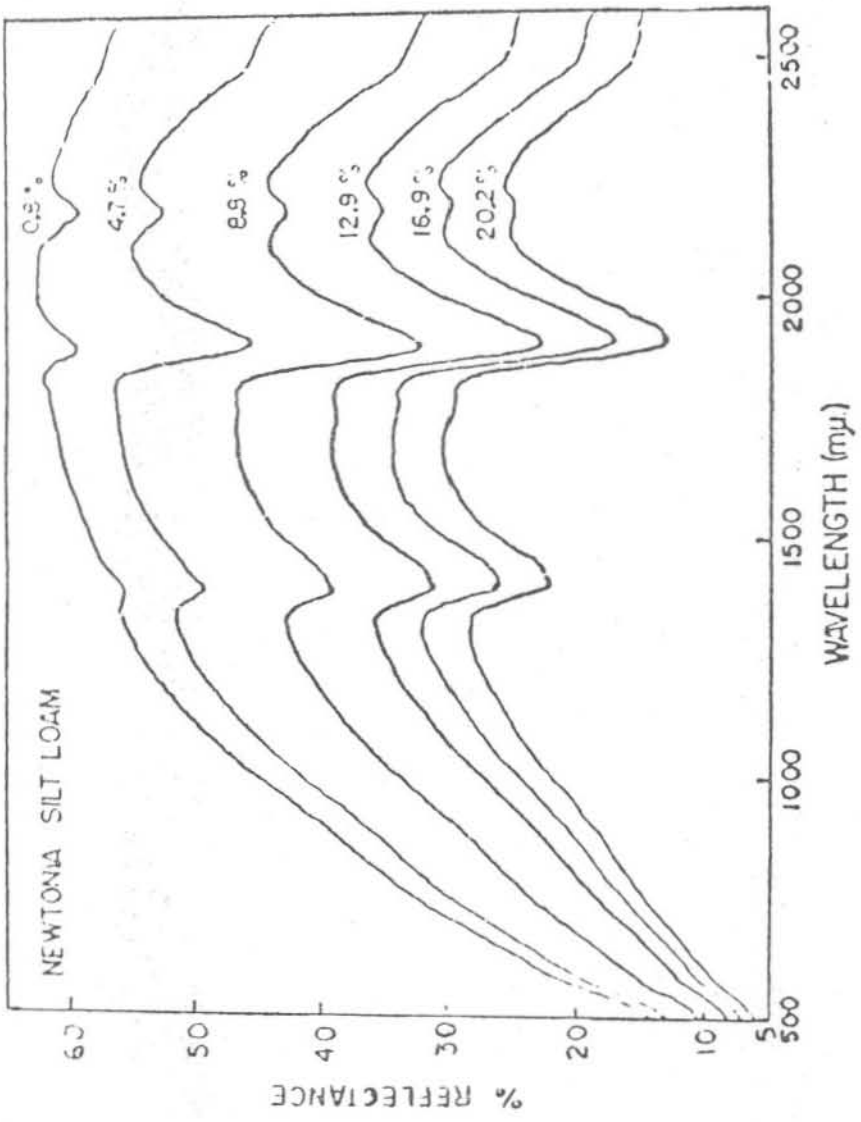

NEWTONA SILT LOAM
0.3 %
4.7 %
8.9 %
12.9 %
16.9 %
20.2 %
% REFLECTANCE
60
50
40
30
20
10
5
500
1000
1500
2000
2500
WAVELENGTH (mμ)

Fig. 3

Fig. 4 - Percent reflectance vs. wavelength of incident radiation for montmorillonite (from Hunt and Salisbury, 1970).

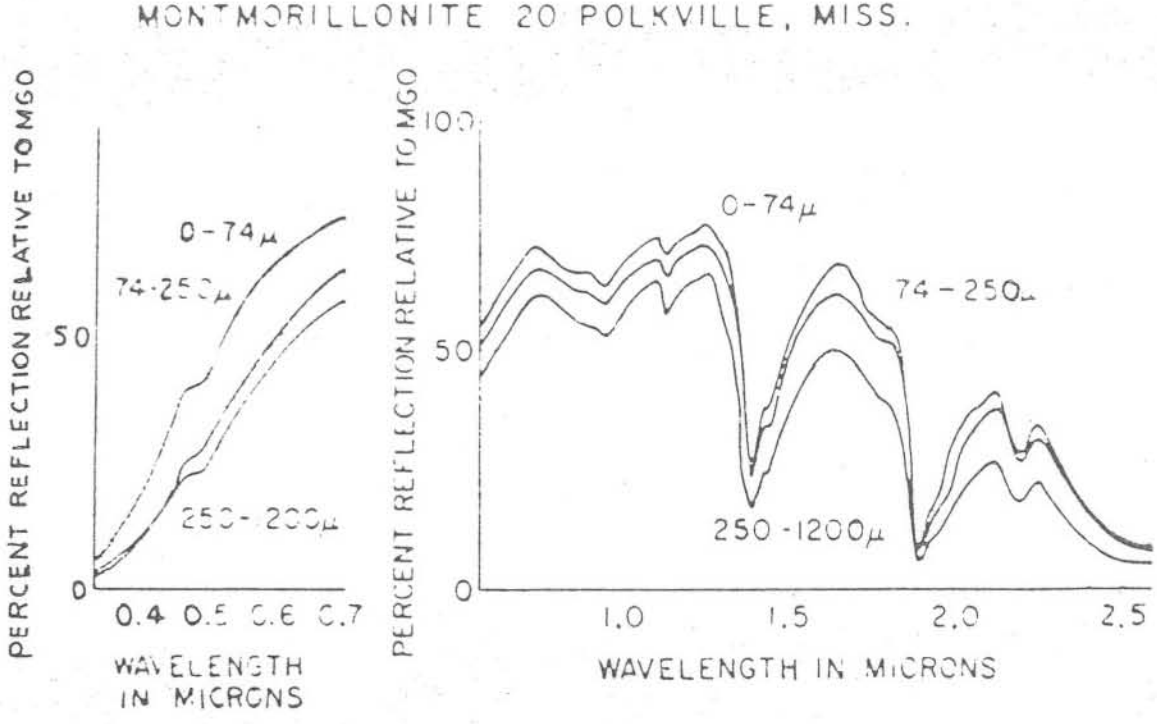

MONTMORILLONITE 20 POLKVILLE, MISS.
PERCENT REFLECTION RELATIVE TO MGO
50
0
0-74μ
74-250μ
250-200μ
0.4 0.5 0.6 0.7
WAVELENGTH IN MICRONS
PERCENT REFLECTION RELATIVE TO MGO
100
50
0
0-74μ
74-250μ
250-1200μ
1.0
1.5
2.0
2.5
WAVELENGTH IN MICRONS

Fig. 4

Fig. 5 - Percent reflectance vs. wavelength of incident radiation for kaolinite (from Hunt and Salisbury, 1970).

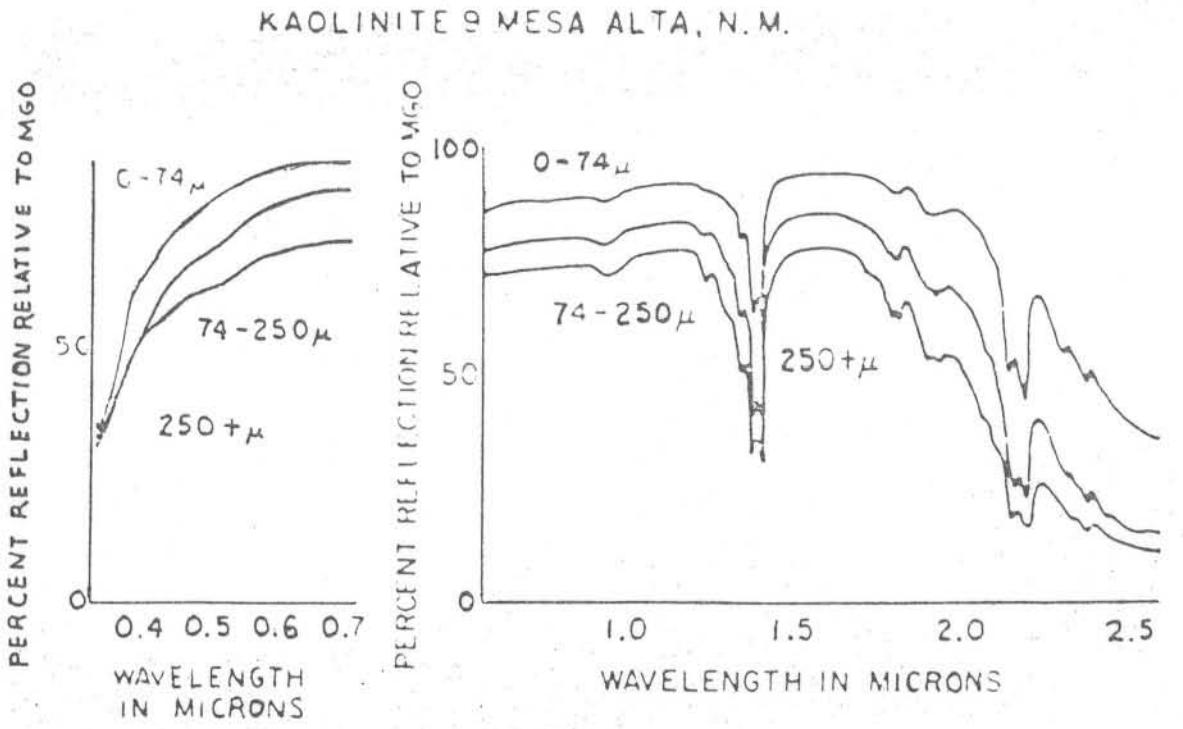

KAOLINITE 9 MESA ALTA, N.M.
PERCENT REFLECTION RELATIVE TO MGO
0-74μ
74-250μ
250+μ
50
0
0.4 0.5 0.6 0.7
WAVELENGTH IN MICRONS
PERCENT REFLECTION RELATIVE TO MGO
100
0-74μ
74-250μ
250+μ
50
0
1.0
1.5
2.0
2.5
WAVELENGTH IN MICRONS

Fig. 5

frequencies which occur in the mid- and far-infrared.

In the visible range the color imparted to a material may be due to the occurrence of specific absorptions in this region, or the color may be caused by intense absorptions in either or both the ultraviolet and infrared and their shoulders may extend forward and backward into the visible. This will impart a color to the material without its having any specific chormomorphic group absorbing energy in the visible region (Hunt and Salisbury, 1970).

The water molecule is very commonly associated with rocks and minerals. According to Hunt and Salisbury (1970) water molecules have three fundamental vibration modes and all are infrared active. They are ν_1, the symmetric OH stretch; ν_2, the H-O-H bend; and ν_3, the asymmetric OH stretch. In a vapor, transmission spectrum bands due to these modes occur at 2.73 μm (3651.7 cm^{-1}), 6.269 μm (1595 cm^{-1}) and 2.66 μm (3755.8 cm^{-1}) respectively. In the liquid phase these bands shift to 3.106 μm (3219 cm^{-1}), 6.08 μm (1645 cm^{-1}), and 2.903 μm (3445 cm^{-1}). In ice the corresponding fundamentals appear at 3.105 μm (3220 cm^{-1}), 6.06 μm (1630 cm^{-1}), and 2.941 μm (3400 cm^{-1}). The unusually large shifts in the corresponding frequencies illustrate that hydrogen bonding has taken place in ice and the observation that the two stretching modes, ν_1 and ν_3, have considerably lower values in the liquid and solid than in gas, while ν_2, the bending mode has a somewhat higher value. In the spectra of minerals and rocks, whenever water is present, two characteristic bands appear at 1.4 μm due to 2 ν_3 overtones and at 1.9 μm due to

$(H_2O)_3$ overtones. When they are well defined bands it usually indicates that the water molecules are located in well defined, ordered sites. When they are broad bands it indicates they are relatively unordered and/or that more than one type of site is occupied by the water molecules. The presence of both the 1.4 and 1.9 μm bands together is diagnostic of undissociated water molecules in the structure, i.e., water of hydration. The appearance of the 1.4 μm band without the 1.9 μm band indicates that OH groups other than those in water are present in the material, i.e., hydroxyls (Hunt and Salisbury, 1970).

Lindberg and Snyder (1972), using the same instrument model as Hunt and Salisbury (1970), examined the spectral reflectance curves of several clay minerals and found the same characteristic curves for montmorillonite (Fig. 6) and kaolinite (Fig. 7) as Hunt and Salisbury (Fig. 4 and 5). They also studied illite but did not publish any spectral reflectance curves even though the spectra were quite different from the other two clay minerals, however, Mathews (1972) did publish a spectral reflectance curve for illite (Fig. 8) and it fits the verbal description given by Lindberg and Snyder (1972). It has a much lower reflectance at any wavelength than either montmorillonite or kaolinite.

Organic matter has been demonstrated to affect the spectral reflectance of soils (Bowers and Hanks, 1965; Mathews, 1972) by scanning them before and after being treated with hydrogen peroxide (Figs. 9 and 10). Regardless of the type of clay present,

Fig. 6 - Changes in the spectral reflectance of montmorillonite as a result of changes in hydration state. Curve (a) original sample; (b) after heating sample to 120°C; (c) after heating sample to 600°C; (d) sample from curve (b) after humidification for two weeks; (e) sample from curve (c) after humidification for two weeks (from Lindberg and Snyder, 1972).

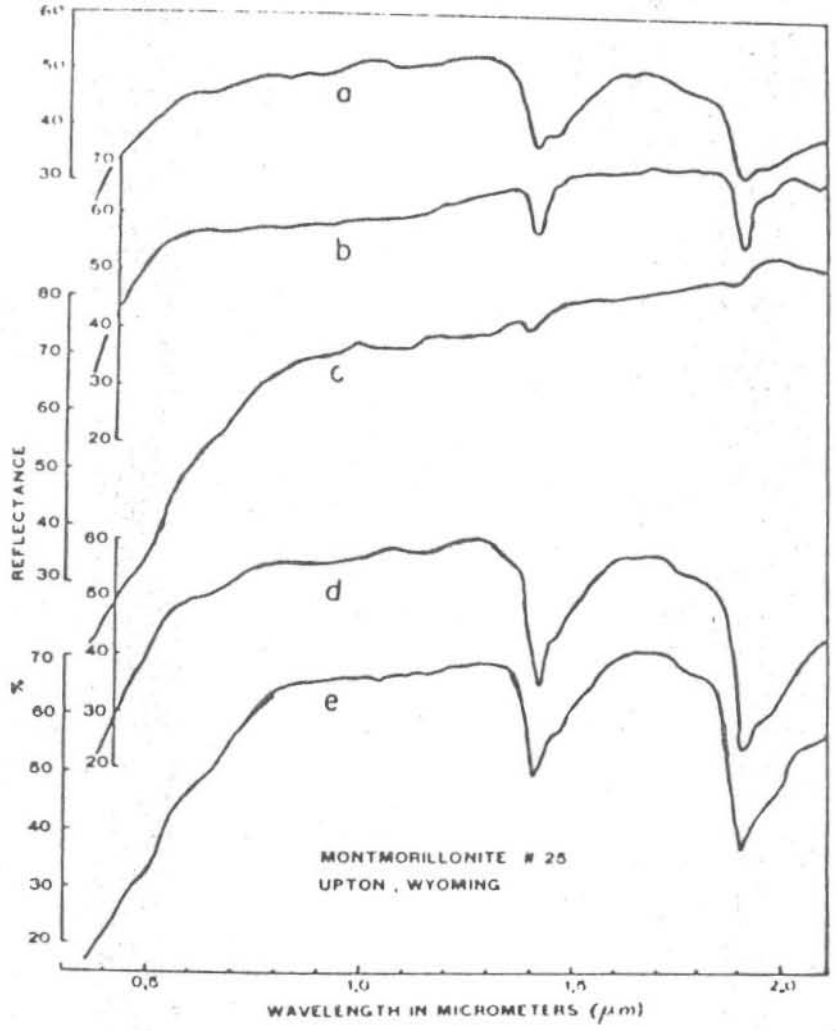

a
b
c
d
e
REFLECTANCE
%
MONTMORILLONITE # 25
UPTON , WYOMING
0,5
1,0
1,5
2,0
WAVELENGTH IN MICROMETERS (μm)

Fig. 6

Fig. 7 - Changes in the spectral reflectance of kaolinite as a result of changes in hydration state. Curve (a) original sample; (b) after heating to 600°C; (c) sample from "curve" (b) after humidification for two weeks (from Lindberg and Snyder, 1972).

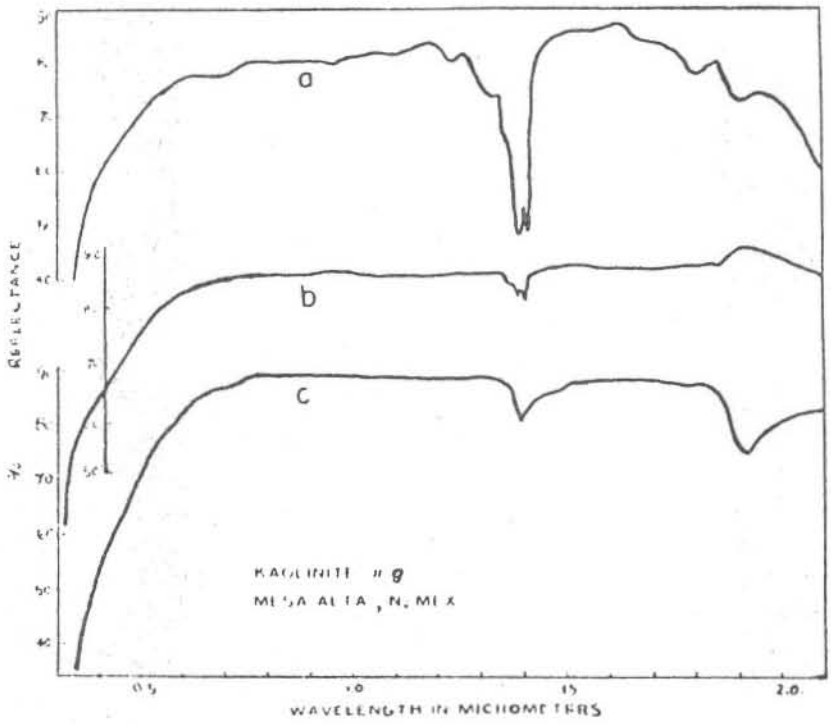


Fig. 7

Fig. 8 - Percent reflectance vs. wavelength of incident radiation for kaolinite, montronite, and illite (from Mathews, 1972).

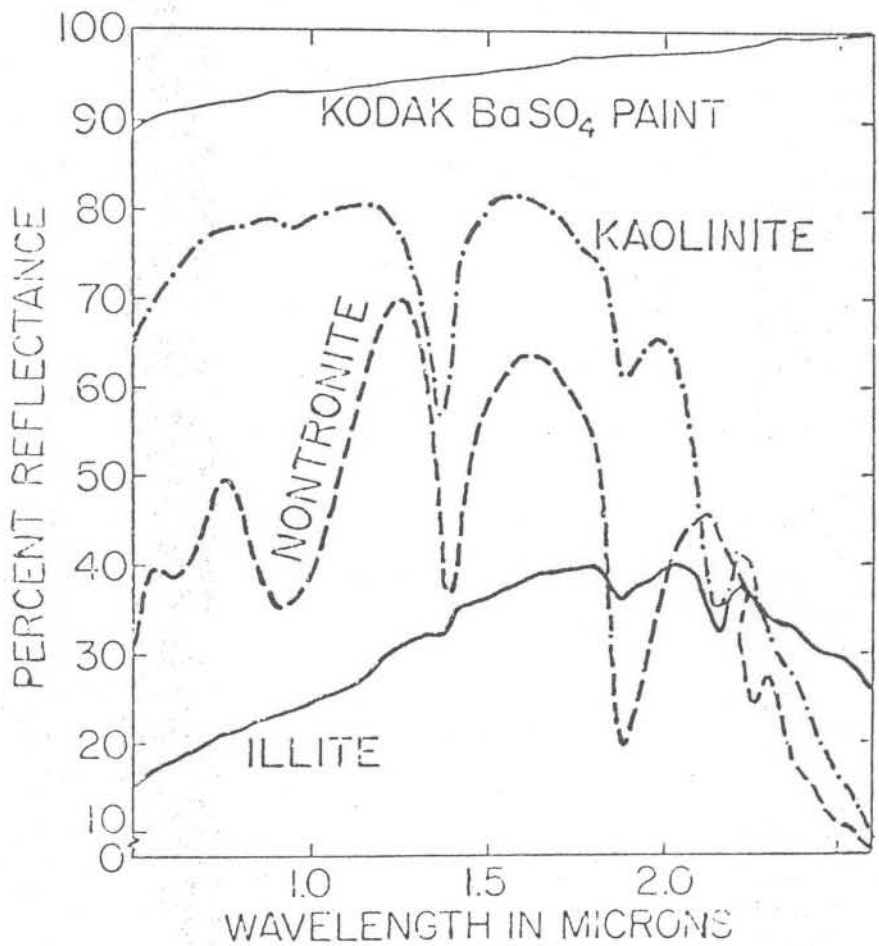
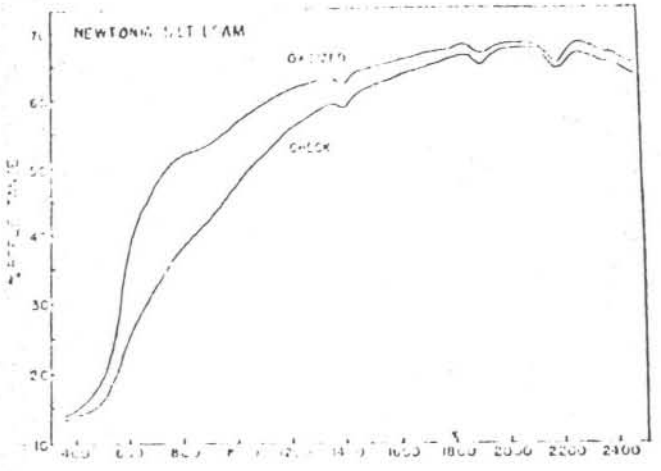
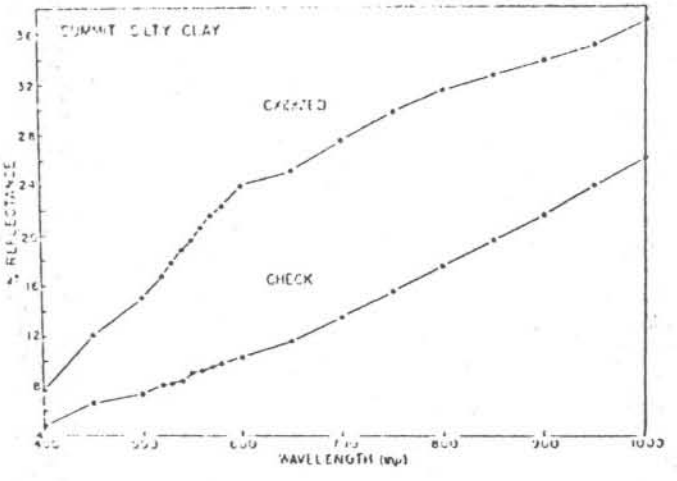

100
90
80
70
60
50
40
30
20
10
0
PERCENT REFLECTANCE
KODAK BaSO4 PAINT
KAOLINITE
MONTRONITE
ILLITE
1.0
1.5
2.0
WAVELENGTH IN MICRONS

Fig. 8

Fig. 9 - Percent reflectance vs. wavelength of incident radiation for H_2O_2 oxidized and check samples of Newtonia silt loam "(a)" and Summit silty clay "(b)" (Bowers and Hanks, 1965).


NEWTONIA SILT LOAM
CHECK

a)


SUMMIT SILTY CLAY
CHECK
% REFLECTANCE
WAVELENGTH (mμ)

b)

Fig. 9

Fig. 10 - Percent reflectance vs. wavelength of incident radiation for H_2O_2 oxidized and check samples of Ellery silty clay and iron oxide removed and check samples of Hagerstown silt loam (from Mathews, 1972).

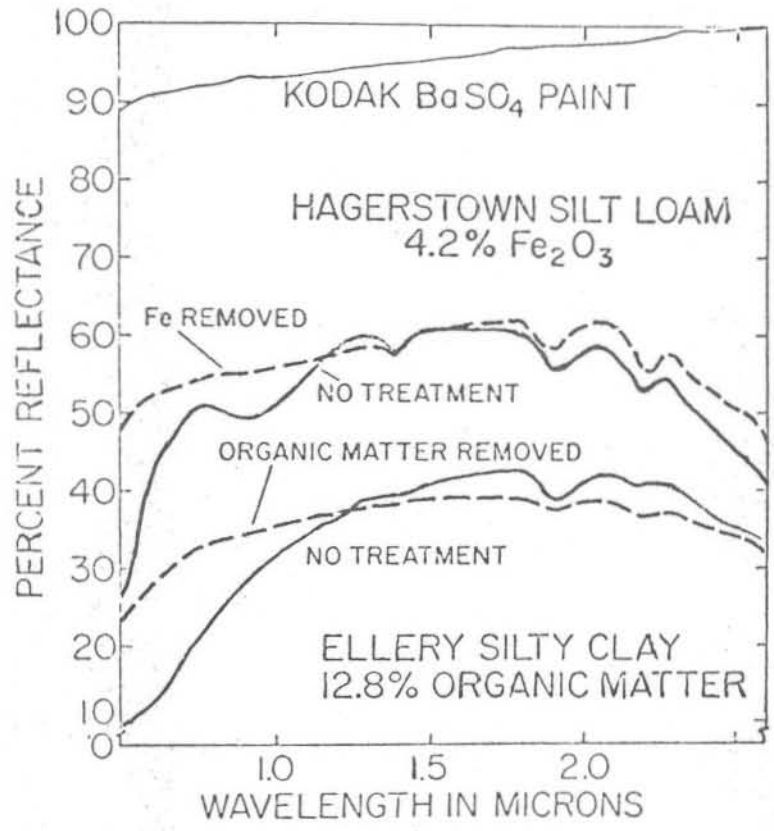

100
90
80
70
60
50
40
30
20
10
0
PERCENT REFLECTANCE
KODAK BaSO4 PAINT
HAGERSTOWN SILT LOAM
4.2% Fe2O3
Fe REMOVED
NO TREATMENT
ORGANIC MATTER REMOVED
NO TREATMENT
ELLERY SILTY CLAY
12.8% ORGANIC MATTER
1.0
1.5
2.0
WAVELENGTH IN MICRONS

Fig. 10

the organic matter seems to lower the spectral curve in all wavelengths with no well defined absorption bands (Figure 9). But, the greatest difference in the amount of energy reflected between the oxidized and unoxidized samples is from .7-1.3 μm (Figs. 9 and 10).

Particle size also influences the spectral reflectance of soils (Bowers and Hanks, 1965; Hunt and Salisbury, 1970). As the particle size of pure clays decreased, spectral reflectance increased. Bowers and Hanks (1965) calculated, with increasing particle size from 22 to 2650 μm, at least an additional 14.6 percent of the direct solar radiant energy would be absorbed. Although no measure of surface roughness was made, it was apparent that as particle size decreased, the surfaces became smoother and reflected more energy indicating that roughness of the surface is a function of the particle size.

Iron seems to influence the spectra of minerals (Fig. 10) at the .9 μm region (Hunt and Salisbury, 1970; Mathews, 1972) but not to the extent the previously mentioned properties do. Montgomery found that iron (Fe_2O_3) didn't significantly explain the variation in spectral reflectance at any wavelength from .37-2.32 μm (Montgomery and Baumgardner, 1974).

After Bowers and Hanks (1965) conducted their study, several individuals attempted to use their information to help classify soils. Shields conducted a study of several Ap horizons in an attempt to distinguish between the Dark Gray Chernozemic and Dark Gray Wooded Great Groups (Canadian Soil Survey) based on their soil color (Shields et al., 1968). He used a Bausch and Lomb

Spectronic 600 with an ultraviolet attachment. Percent organic carbon was determined by dry combustion and ranged from 1.01-6.02%. He found that moisture had no effect on the hue or chroma of the soils studied, but the value of Gray Wooded soils decreased when moistened from air dry to field capacity by 1.5-2.0 units compared to 1 unit for Chernozems. The reflectance in the ultraviolet region was satisfactory in distinguishing between the two soil classes. Another study, by Page (1974), estimated organic matter percentage in 96 coastal plain soils. Using a Hunterlab Model D25D2M calibrated with two reflectance standards (94.5% and 21.3% reflectance), air-dried samples passing a 12 mesh sieve were scanned in the visible portion of the spectrum. Reflectance values were highly correlated (r .89) with soil organic matter by Walkley-Black method within the 0-5% organic matter range. These laboratory studies indicate the potential for mapping soil organic matter or carbon values in the field with remote sensors.

Condit (1970) attempted to classify the spectral reflectance curves of 160 soils from several states. He used the Cary Model 14 recording spectrophotometer to measure reflected radiation from .3 to 1.0 μm. He was able to classify the 160 soils into three general types based on the shape of their spectral curves. Partially using the 1938 soil classification system, the three classes were Chernozems, Pedalfer-type silts, and red quartz and calcite sands. The necessity of extending spectral reflectance measurements to 1.0 μm or beyond was noted because several samples have spectral curves of similar

shapes in the ultraviolet and visible portions of the spectrum but are quite different in the infrared. A study using Exotech 20-C was made on soils of Tippecanoe County, Indiana, with similar results (Cipra et al., 1971).

In the early 1970's, the Laboratory for Application of Remote Sensing (LARS) at Purdue University and Environmental Research Institue of Michigan (ERIM) at Ann Arbor first attempted to use remotely sensed data from field spectroradiometers (Exotech 20-C) and aircraft scanners. These attempts to classify soils were based on the preliminary results obtained by Bowers and Hanks (1965) and Condit (1970).

Even with this information, most of the wavelength bands selected for attempting to classify soils with remote sensors by the researchers at LARS, ERIM and other laboratories, were clustered in the visible region (Table 1).

Investigators at LARS have used the information gathered by the ERIM multispectral scanner from soil test areas 2-6 located in Indiana to map soil series, organic matter, clay, texture and various other soil properties from about 3,000-5,000 ft (Al-Abbas et al., 1972; Baumgardner et al., 1970; Baumgardner and Staff, 1972; Cipra et al., 1972; Horvath et al., 1971; Kristof, 1971; Kristof and Baumgardner, 1972; Kristof and Zachary, 1974; Stoner et al., 1972; West, 1972; Zachary et al., 1972). Soil test areas numbered 2 and 3 are developed in late Wisconsin-age, glacial material including till, outwash and aeolian soils, located in the central part of

Table 1. Some ERIM aircraft, multispectral scanner channels used in research at LARS.

Channel Number	Wavelength Range Covered (μ m)			
	A*	B*	C*	D*
1	.40- .44	.46- .49	.40- .44	.40- .44
2	.46- .48	.48- .51	.44- .46	.44- .46
3	.50- .52	.50- .54	.52- .55	.46- .48
4	.52- .55	.52- .57	.55- .58	.48- .50
5	.55- .58	.54- .60	.58- .62	.50- .52
6	.58- .62	.58- .65	.62- .66	.52- .55
7	.62- .66	.61- .70	.66- .72	.55- .58
8	.66- .72	.72- .92	.72- .80	.58- .62
9	.72- .80	1.00-1.40	.80-1.00	.62- .66
10	.80-1.00	1.50-1.80	1.00-1.40	.66- .72
11	1.00-1.40	2.00-2.60	1.50-1.80	.72- .80
12	1.50-1.80		2.00-2.60	.80-1.00
13	2.00-2.60			

A* Baumgardner and Staff. LARS, Information Note 012672; Baumgardner and Kristof, Lars Print 102372.

B* Stoner, Baumgardner, Anuta, and Cipra, LARS Print 111372.

C* Zachary, Cipra, Diderickson, Kristof, and Baumgardner, LARS Print 110972; Al-Abbas, Swain, and Baumgardner, Soil Science, 114(6):478; Horvath, Montgomery and Van Zile, Indiana Academy of Science, 80:479; Baumgardner, Kristof, Johannsen, and Zachary, LARS Information Note 030570.

D* Kristof and Zachary, Photogrammetric Engineering, 40(12): 1428.

Indiana in Morgan County. Soil test areas 4, 5, and 6 are located in Tippecanoe County, Indiana, and have soils developed in 18 to 36 inches of silt overlying glacial till.

The wavelength bands in which spectral reflectance data was collected with the ERIM multispectral scanner seem to have been chosen without regard to findings of Bowers and Hanks (1965), Condit (1970), or Hunt and Salisbury (1970) who suggested certain wavelength bands in the infrared might offer more information about soil properties than bands in the visible region. Notice the majority of bands chosen in the visible region (<.72 μm) versus the number of bands in the near infrared (Table 1). The wavelength regions most sensitive to water (1.4 and 1.9 μm), hydroxols (2.2 μm) and organic matter (.7-1.3 μm) are often separated or partially recorded.

Even though the multispectral scanners were not set to measure the spectral regions that are most affected by soil properties, the attempts at mapping soil series has been demonstrated as somewhat successful by Zachary et al. (1972), Kristof and Zachary (1974) and Cipra et al. (1972). One of the problems mentioned in these studies has been the inability to distinguish between sandy soils and silt loam soils when they are light colored, possibly because the water absorption bands are scanned separately with some loss of information when only one of the channels sensitive to water are used in the analysis to classify the soils.

Others have attempted to classify soils other than by series, such as vegetated and non-vegetated soils, soil color (Kristof, 1971), different parent materials and erosion classes (Mathews et al., 1973), and engineering properties (West, 1972). Kristof concluded from his preliminary study of soils in Morgan County, Indiana, that actual surface moisture, erosion, organic matter content and surface roughness factors would have greatly aided the interpretation of the data. It seemed to others that if these items would have aided the interpretations of field data, that these items could possibly be mapped using the spectral data gathered. Mathews et al. (1973) found this could be done somewhat successfully in their study in southeastern Pennsylvania. The soils that had developed in sandstone parent materials were correctly identified 96% of the time while other soils developed in alluvium were correctly identified 55% of the time. When West (1972) attempted to classify sandy floodplain soils versus till plain soils, 76% correct discrimination was made between the two soils. So attempts at soil classification with remote sensors looks promising but accuracy is not as high as hoped.

In an attempt to determine which soil properties affect the spectral reflectance curves of soils in the field, investigators measured the effect of altitude on mapping soil organic matter, related organic matter and clay content to the multispectral radiance of soils, and measured the effects of organic matter on the multispectral properties of soils (Horvath et al., 1971; Al-Abbas

et al., 1972; Baumgardner et al., 1970). But, again notice the lack of chosing wavelength bands (Table 1) sensitive to soil properties suggested earlier by Bowers and Hanks (1965), Condit (1970) and Hunt and Salisbury (1970).

All of these studies used multiple regression analysis to determine the strength of the relationship between spectral response and the soil property of interest. Horvath et al. (1971) found the multiple correlation coefficient to be .76 when using all 12 channels and the spectral data collected at 5,000 feet. The channel most highly correlated with organic matter was .72-.80 μm. Baumgardner et al. (1970) found correlation coefficients of .74 for organic carbon content and spectral response using linear multiple regression analysis. They also suggested that a linear relationship may not be valid but a quadratic relationship might be valid over the range of organic matter utilized, and above and below 2 percent organic matter there is a difference in the slope of the curve.

In a later study with the same data, Al-Abbas et al. (1972) were able to increase the r^2 values for organic carbon versus spectral response from .526 to .560 with a second order quadratic. When it was applied to percent clay versus spectral response at 1.00-1.40 μm, the quadratic increased the r^2 from .405 to .505. They suggest that the relationship between clay content and relative reflectance is not clearly defined and might be secondary as a result of the high correlation of organic matter and clay content.

In a different study area similar to the one just mentioned, Baumgardner and Staff (1972) found the correlation coefficient between organic matter and spectral response to be .70 after geometric correction of the data was made. Based on their study, three channels in the visible (.55-.58 μm; .62-.66 μm; .66-.77 μm) and one channel in the infrared (.80-1.00 μm) gave these high correlation coefficients.

Other attempts have been made to increase the accuracy of mapping soil properties. One such attempt used ratios of selected wavelength bands. Vincent and Thomson (1971) found that if the reflectance measured in a band located at 11.5-13.0 μm was divided into the reflectance from 8-11.5 μm, the ratios would permit the recognition of silicate minerals as a group from most non-silicate targets. Once the silicates had been separated from non-silicates, the amount of silica present could be measured by using the ratio from the reflectance at 8.2-10.9 μm divided by the reflectance at 9.4-12.1 μm.

Dillman and Vincent (1974) found that ratio images and multispectral recognition maps produced from ratio inputs to statistical recognition theory have been found to be useful for geologic remote sensing. Spectral ratios are useful because they 1) enhance the contrast between targets which have interesting spectral reflectance curves; 2) suppress or reduce illumination variations across the scene; and 3) permit acceptable correlations between spectral ratios calculated from field reflectance spectra and laboratory reflectance spectra.

Using the advantage of ratioing to suppress unwanted atmospheric and solar variations, Vincent and Pillars (1974) studied 211 laboratory samples of rocks, minerals, soils, and vegetation to select optimum channels to be used in the Skylab S-192 multispectral scanner. After studying the ratios they found that three of the top four channels (2.10-2.34, .93-1.05, .45-.50 and 1.55-1.75 μm) for mapping rocks, soils and minerals are beyond the infrared spectral range (.9 μm) of photographic film. It was also noted that using the top four ratios (.77-.89/.60-.65, .50-.55/.45-.50, .93-1.05/.54-.60, 1.15-1.28/1.03-1.19 μm) the soils were easily confused with the vegetation samples. This is somewhat difficult to understand since the spectral curves for several green plants illustrated by Hoffer and Johannsen (1969) show there is very little absorption by leaves (Fig. 11) in the three infrared bands selected by Vincent and Pillars which lie between .77-1.28. However, the denominators of these ratios fall within the chlorophyll absorption bands of the visible region possibly accounting for part of the difficulty.

Baumgardner, Kristof and Melhorn (1972) found ratioing of three bands of the 4 ERTS bands to be very useful in mapping six soil associations from ERTS-A remotely sensed data. A problem in the interpretation of the spectral reflectance of soils that was not corrected by ratioing, was the use of uncorrected relative reflectance figure for classification as described by Kristof and Baumgardner (1972). In mapping the changes of multispectral soil patterns with increasing crop canopy, the use of uncalibrated data led them to the

Fig. 11 - Percent reflectance vs. wavelength of incident radiation for leaves (from Hoffer and Johannsen, 1964).

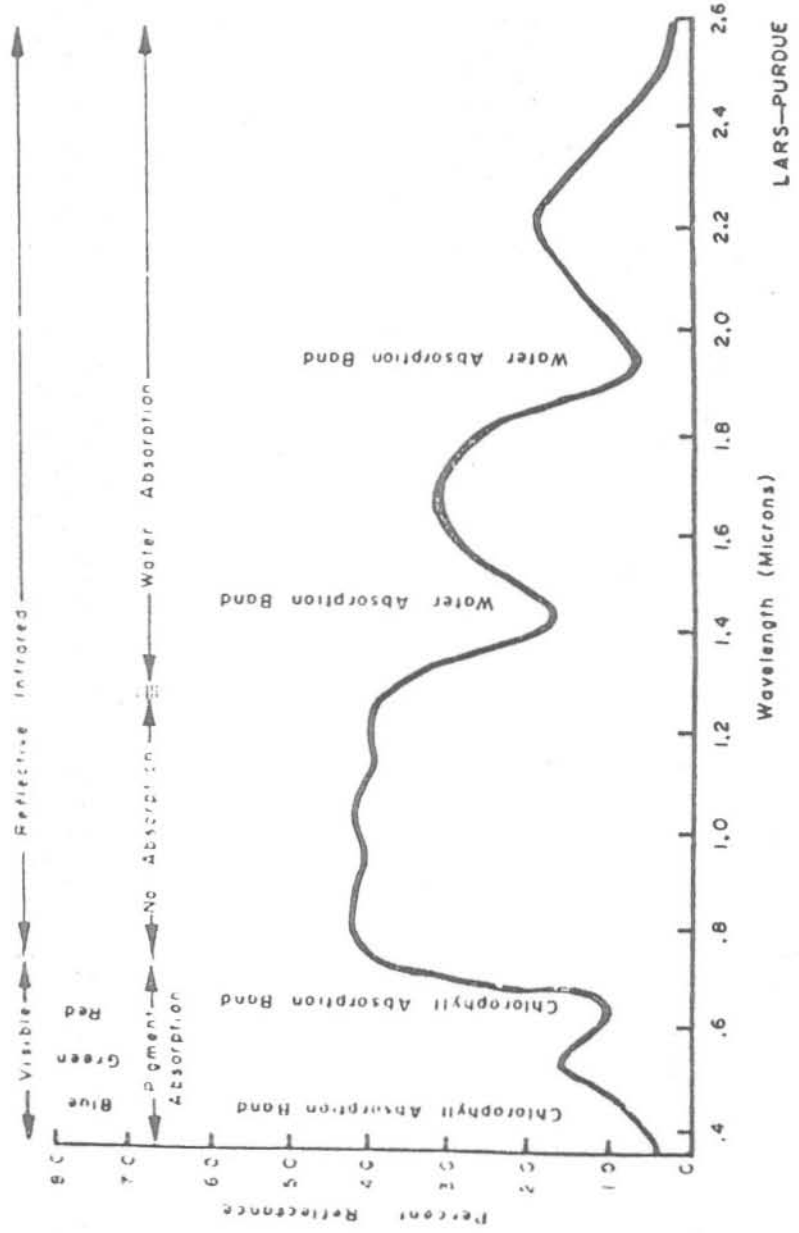

Visible
Reflective Infrared
Blue
Green
Red
Pigment Absorption
No Absorption
Water Absorption
Chlorophyll Absorption Band
Chlorophyll Absorption Band
Water Absorption Band
Water Absorption Band
Percent Reflectance
Wavelength (Microns)
LARS—PURDUE

Fig. 11

opposite conclusion from Hoffer and Johannsen's (Fig. 12). They stated that since non-vegetated soils absorb relatively little energy in the visible spectrum and relatively more in the infrared spectrum, the highest ratio values were in the bare soil when dividing the reflectance from .58-.62 µm by the reflectance from .80-1.00 µm. An attempt to avoid this type of error was made in a study by Stoner et al. (1972). They calibrated the ERIM multispectral scanner by the use of reflectance panels placed in close proximity to the silt loam plots studied. When the scanner data was calibrated by the use of these panels the spectral curve of the bare soil plots took the shape described by Bowers and Hanks (Fig. 3) and others.

The computer programs have been successfully developed which enable researchers to use automatic data processing in the classification of soil properties. With the approaches taken to correct scanner data and the use of ratios the accuracy of mapping soil properties is still not as great as many of the researchers cited would like. My study is approached with the information provided by the basic researchers, Bowers, Hanks, Hunt, Salisbury and others in mind. Reports have been presented showing the spectral characteristics of organic carbon in soils before and after oxidation and the effects of soil moisture on the spectral response of clays, but no one has studied the specific interaction between soil moisture and organic carbon in soils controlled moisture levels and identify the wavelength bands most affected. That is the purpose of this thesis.

Fig. 12 - Percent reflectance vs. wavelength of incident radiation for leaves and water (from Hoffer and Johannsen, 1969).

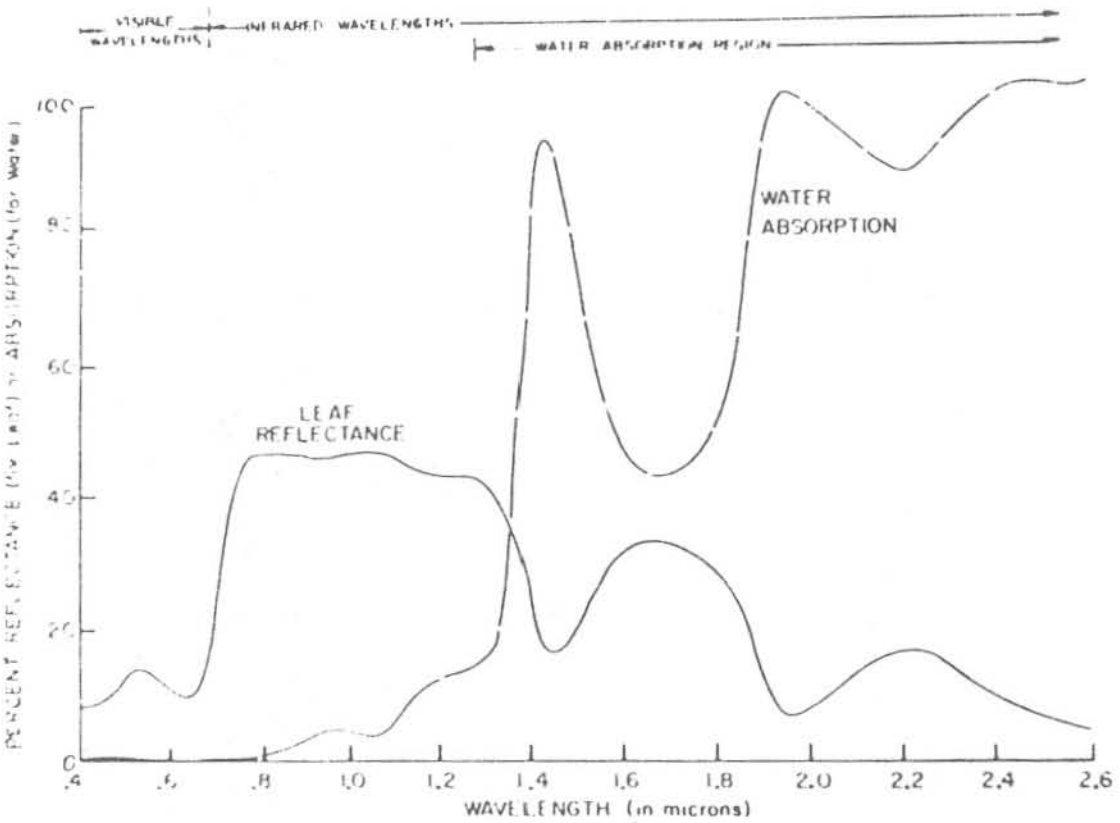

WATER
ABSORPTION
LEAF
REFLECTANCE
100
60
40
20
0
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
WAVELENGTH (in microns)

Fig. 12

MATERIALS AND METHODS

I. Soil Sample Selection

One of the objectives of this study was to determine how much of the variation in spectral responses of soils could be explained by their organic carbon content. To make this determination, soils of the study area were chosen to represent a wide range in organic content.

The Tippecanoe County Soil Survey Report, soil survey laboratory data, and profile descriptions (Forms SCS-421) were studied for estimates of the organic carbon contents in soils of the study area. Black and white aerial photos were used along with the soil survey report to locate the sample areas. Each sampling site, a 4 square meter (2 x 2) area, was sampled to a depth of approximately 3 cm with a flat shovel. All of the soils except two were collected from an area within 8 miles east of the Tippecanoe-Benton and Tippecanoe-Warren County lines and north of the Wabash River.

The soils in the study area were formed on the upland loess (40 inches) over Wisconsin-age, calcareous, loam till. The soils were classified as Udolls, Udalfs, Aqualfs, or Aquolls. The organic carbon content in these surface soils (Ap Horizons) ranged from .60-3.33% and the textures predominately silt loam or silty clay loam (Table 2).

Table 2. Information on the Soil Series.

Soil Series	Parent Material	Catena	Surface Textures	Drainage	Taxonomic Classification
		Prairie			
Sidell	loess over	Sidell	sicl	well	Typic Argiudoll
Dana	loam till		sicl	moderately well	Typic Argiudoll
Raub			sicl	somewhat poorly	Aquic Argiudoll
Chalmers			sic	very poorly	Typic Argiaquoll
Romney			sicl	very poorly	Typic Argiaquoll
		Forest			
Russell		Russell	sil	well drained	Typic Hapludalf
Fincastle			sil	somewhat poorly	Aeric Ochraqualf
Delmar			sil	poorly	Aeric Ochraqualf
Brookston			sic	very poorly	Typic Argiaquoll
Kokomo			sic	very poorly	Typic Argiaquoll
		Prairie			
Parr	loam till	Parr	sicl	well	Typic Argiudoll
Corwin			sicl	moderately well	Typic Argiudoll
Odell			l	somewhat poorly	Aquic Argiudoll
Chalmers			sic	very poorly	
Romney			sicl	very poorly	Typic Argiaquoll
		Forest			
Miami		Miami	sil	well	Typic Hapludolf
Crosby			sil	somewhat poorly	Aeric Ochraqualf
Brookston			sic	very poorly	
Kokomo			sic	very poorly	

II. Physical Characteristics of the Soils

The organic carbon content of the 15 surface soils (Ap Horizons) was measured by three commonly used wet combustion methods, Allison's method of total carbon (Allison, 1965), Mebius' method for organic carbon (Mebius, 1960), and the Walkley-Black method for easily oxidizable organic carbon (Allison, 1965). Since all are frequently used, it was felt that all three methods should be compared using these soils (Appendix A).

The Allison method measures all the carbon present in the soil, both the organic and the inorganic (carbonates) forms. To test for carbonates the soil samples were treated with 4N HCl, a procedure suggested by Allison (Allison, 1965), and no carbonates were detected. Therefore, the values determined by the Allison method were taken as the total organic carbon content. The sample containing approximately 30 mg C is mixed with 1 gram of potassium dichromate and then 25 mls of a 60:40 mix of sulfuric and phosphoric acids is added. The CO_2 evolved from the reaction is trapped in Ascarite and weighed giving results similar to those obtained by dry combustion.

The Mebius method (Mebius, 1960) involves the direct titration of surplus potassium dichromate with Mohr's salt solution after applying external heat and using reflux condensers. This is reported to give results practically identical with those of the dry combustion method and carbonates, if present, do not interfere.

The Walkley-Black method (Allison, 1965) is essentially identical to the Mebius method, except the Walkley-Black method doesn't call for heating the sample externally nor the use of the reflux condensers. According to Allison it determines the easily oxidizable organic carbon.

The soil samples were air dried and crushed by hand to pass all the soil through a 2.38 mm sieve. Each sieved sample was then subsampled using a Cenco Soil Sample splitter. One subsample, approximately 500 grams, was hand crushed using an agate mortar and pestle (when necessary) to pass a .42 mm sieve. The other subsample was ground to pass a .149 mm sieve using a motor driven agate mortar and pestle. Each of the three organic carbon analyses were then performed on the .42 mm and .149 mm sieved soils.

The texture of each soil was determined by mechanical analysis. The clay fraction was determined by the hydrometer method (Bouyoucos, 1962) and the sand fraction was sieved using a .05 mm sieve, dried and weighed.

III. Moisture Equilibration of the Soil Samples

To determine how much of the variation in spectral reflectance of soils could be explained by their water content, subsamples from each soil (approximately 130 grams) were equilibrated at two moisture tensions; 1/3 bar (4.9 psi) and 15 bars (220 psi). After being allowed to equilibrate 48 hours, the samples were spectrally measured in the laboratory using a field spectroradiometer (Exotech 20C), weighed, oven dried and reweighed to determine percent

water at each tension and the oven dried 1/3 bar samples were measured This resulted in spectral measurements of each soil at three moisture tensions. The spectral reflectance curves for each soil sample at 1/3 bar and oven dry were from the same sample because it was desirable to have the same surface roughness on all samples spectrally measured.

Air-dried samples were placed in rubber rings 2 cm deep and 10 cm in diameter and then saturated with water for 16 hours and equilibrated at 1/3 bar in a pressure plate apparatus for 48 hours. Separate air dried samples were placed in similar rubber rings, saturated and allowed to equilibrate at 15 bars in a pressure membrane apparatus for the same length of time as the 1/3 bar samples. All samples were later oven dried at 105°C for 48 hours in a forced air drying oven and exposed to the atmosphere only during spectral measurement (2 minutes).

IV. Spectral Measurements of the Soils

After the soils had equilibrated at the desired moisture tension, they were spectrally measured indoors over the range from .53 microns to 2.32 microns using a field spectroradiometer (Exotech 20-C) with collimated illumination provided by a specially housed General Electric 6XW lamp and a spherical mirror (Fig. 13). The spectroradiometer has a short wavelength head (.37-2.5 μm) and a long wavelength head (2.8-14 μm). The short wavelength head was used and has two detectors. The silicon detector covers the wavelength 0.35 to 0.70 μm and the lead sulfide detector uses a circular

Fig. 13 - Diagram of Exotech 20-C laboratory set up (from DeWitt and Robinson, unpublished).

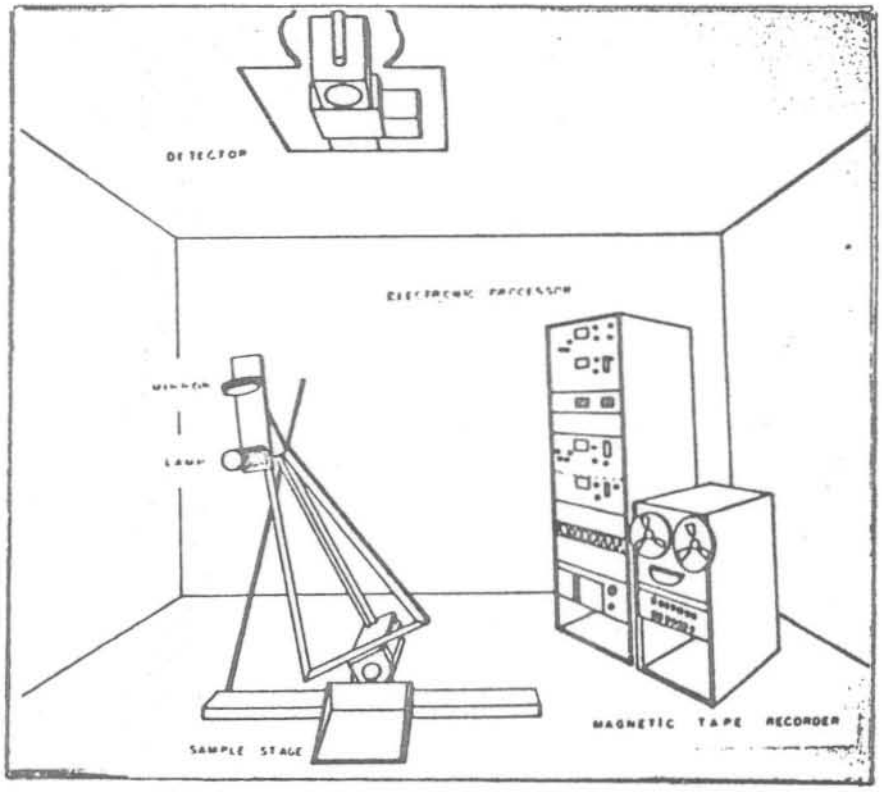

DETECTOR
ELECTRONIC PROCESSOR
MIRROR
LAMP
SAMPLE STAGE
MAGNETIC TAPE RECORDER

Fig. 13

variable filter to cover two wavelength ranges, 0.65 to 1.30 μm and 1.25 to 2.5 μm (Cipra, Silva and Hoffer, 1971).

To calibrate the instrument, pressed Barium Sulfate, a perfect diffuser, is measured spectrally. After every fifth sample, the standard, Barium Sulfate, is measured and the ratio of the sample response to the standard is multiplied by a correction factor, to correct for changes in sensitivity of the detector. The ratio can be converted to percent reflectance by multiplication by pi (π) if two assumptions are true; (1) the standard is a perfect diffuser and (2) the sample is a perfect diffuser (DeWitt and Robinson, unpublished). If both assumptions are not true then multiplication by π is still the best estimate and the result is called the reflectance factor. If the ratio is not converted to percent reflectance the ratio is referred to as Rho-Prime (P') and is the unit accepted by the National Bureau of Standards for energy being measured. The relationship between percent reflectance and P' is as follows: 100% reflectance is equal to π times P', 31.8 for Barium Sulfate. The values recorded consist of six complete scans covering the entire wavelength range measured and when these values are digitized and processed, the average of these six scans are reported as P'.

The high intensity lamp used for inlab experiments has different properties than solar radiation (Fig. 2). There are several bands in the infrared region that reflect little solar energy due to absorption by water in the atmosphere, but the lamp has energy in these bands so extrapolation of laboratory results to the field must be made carefully.

RESULTS AND DISCUSSION

The measured physical properties of the soils used to explain the variation are presented in Table 3. The organic carbon content of the samples ranges from .60 to 3.33% with no clustering of data and a mean of 1.55% by the Allison method using soil crushed to 0.149 mm diameter. The textures were predominantly silt loams and silty clay loams as seen in Table 3 with a mean of 14.2% sand, 55.4% silt, and 30.4% clay. These samples are representative of mid-western soils developed in loess over glacial till, but the interpretations are somewhat limited in many soil regions because of the limited textural range. Moisture has been shown to dominate the spectral reflectance of soils over the electromagnetic spectrum from .38 μm to 2.5 μm (Lindberg and Snyder, 1972), therefore measurements were at three tensions of agronomic interest; oven dry, 1/3 bar and 15 bars. Percent water by weight (dry weight basis) is reported in Table 3 with a mean of 10.5% retained by these soils at 15 bars and a mean of 27.3% at 1/3 bar.

The physical properties affect the spectral reflectance (Munsell color notations) in the visible region as can be readily seen in Table 3, especially organic carbon content and moisture. The Munsell color notations of these soils show a general trend of lighter values with decreasing organic carbon content when the samples are air dry, but when moistened they order themselves almost

Table 3. Physical properti[illegible] Soil Series.

Soil Series	% Organic Carbon (n=4)	% Sa[illegible] (n=[illegible])	% Silt (n=2)	% Clay[c] (n=2)	Munsell Color Notation Dry (n=4)	Moist (n=4)	% Water 15 bar (n=2)	% Water 1/3 bar (n=2)	Textural Class
Chalmers	3.33	5.[illegible]	51.3	43.4	10YR3/1	10YR2/1	16.69	32.66	sic
Corwin	2.66	12.[illegible]	54.8	32.6	4/2	2/1	14.54	28.40	sicl
Romney	2.64	10.1	50.5	39.4	3/1	2/1	17.05	34.54	sicl
Kokomo	1.84	2.9	56.4	40.7	5/2	3/2	12.70	33.86	sic
Parr	1.83	15.[illegible]	55.0	29.2	4/2	3/1	10.47	27.28	sicl
Dana	1.55	12.[illegible]	58.2	29.2	4/2	3/1	10.38	24.74	sicl
Sidell	1.47	11.[illegible]	56.8	31.6	5/2	3/2	10.56	29.02	sicl
Brookston	1.47	14.2	45.6	40.2	4/2	3/1	13.14	26.87	sic
Crosby	1.32	9.7	64.5	25.8	5/2	3/2	8.11	25.96	sil
Odell	1.25	32.[illegible]	44.0	23.4	4/2	3/1	8.78	23.42	l
Raub	1.14	13.[illegible]	55.4	30.8	5/2	3/1	9.52	27.12	sicl
Russell	.86	14.[illegible]	61.0	24.2	5/2	4/2	7.00	24.66	sil
Miami	.66	13.4	63.8	22.8	6/3	5/2	6.21	24.56	sil
Fincastle	.63	20.2	55.2	24.6	6/3	4/2	7.68	23.56	sil
Delmar	.60	23.6	58.8	17.6	6/3	5/3	4.48	22.62	sil

a Allison 100 mesh

b by sieve

c by hydrometer

perfectly from darkest to lightest values with decreasing organic carbon content. Moisture affects Munsell color values most often and chromas next agreeing with Shields et al. (1968).

Continuous spectral curves were recorded on magnetic tape (Exosys Tape No. 3122, Run Numbers 74312300-74334000, experiment no. 74100601, Laboratory for Application of Remote Sensing, West Lafayette, IN) and analysis was conducted by breaking these continuous spectral curves into narrow segments or bands. The results of previous experiments at LARS (personal communication with Jan Cipra) led to the selection of 57 bands, .03 and .04 μm wide for use in the analysis.

A representative sample of the spectral reflectance curves is that of Brookston silty clay loam (Figure 14). The first segment is the section scanned by the silicon detector, the second and third segments are scanned by the lead sulfide detector with the circular variable filter rotating in front of the lead detector. As with any recording instrument the data recorded at the extreme ends of any segment are not as accurate as the center section, so the data nearest those changes was not used.

All the samples measured have a shape similar to that of montmorillonite as shown by others (Hunt and Salisbury, 1970; Lindberg and Snyder, 1972; Mathews, 1972), and the overall spectral reflectance increases from the visible to the infrared wavelength regions as suggested previously (Bower and Hanks, 1965; Mathews, 1972).

Fig. 14 - Percent reflectance vs. wavelength of incident radiation for Brookston silty clay loam.

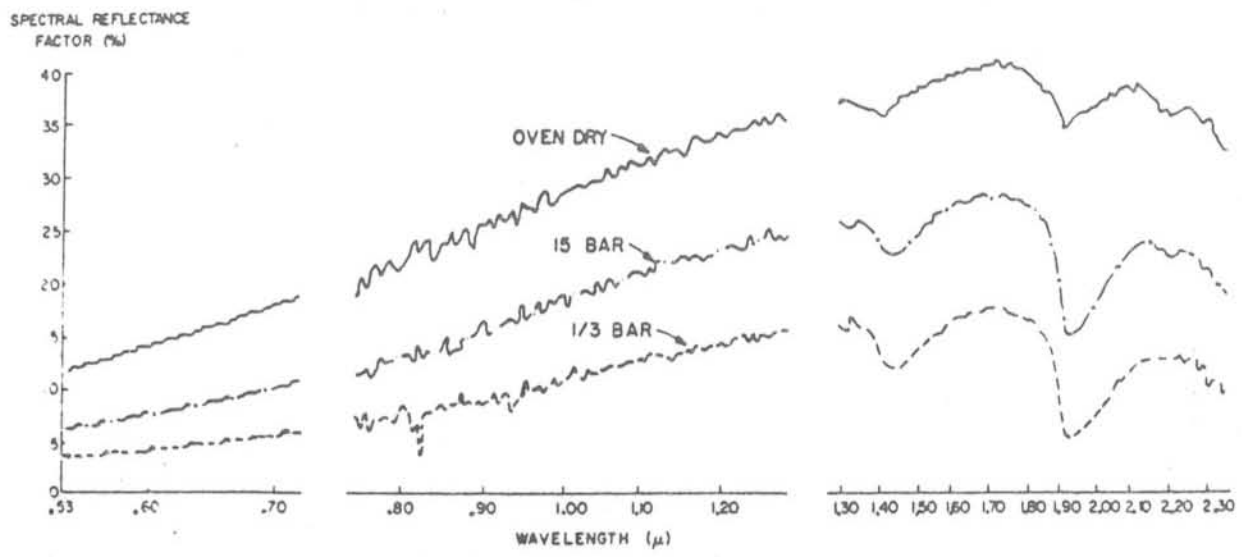

SPECTRAL REFLECTANCE
FACTOR (%)
40
35
30
25
20
15
10
5
0
.53
.60
.70
OVEN DRY
15 BAR
1/3 BAR
.80
.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00
2.10
2.20
2.30
WAVELENGTH (μ)

Fig. 14

In assessing the effect of the soil properties on the spectral response a stepwise, forward selection, multiple regression program was used (STEPR). The average spectral reflectances (P') from two replications of each soil in every band was used as the dependent variables and the soil properties the independent variables. The coefficient of determination (r^2) was then plotted on the ordinate and the band widths on the abscissa as in Figures 15 through 21.

The experiments were designed to study the effects of soil organic carbon content and moisture on the spectral reflectance properties of soils. It was first proposed that different methods of determining percent organic carbon might have a significant affect upon the regression of organic carbon versus spectral response. This is of concern since the three methods used are commonly used in soil analysis. There was no significant difference among the three methods in explaining the variation in spectral response as shown in Table 4. The values obtained from .149 mm soil by the Allison method will be the organic carbon values discussed in the rest of this paper.

In attempting to describe which wavelength bands are affected most by the soil property measured, single regression analyses were made with spectral response versus each soil property. Figure 15 has three curves showing the r^2 values (of organic carbon versus spectral reflectance) at each wavelength band, each curve representing one of the three moisture levels. Organic carbon explains the variation in spectral reflectance most effectively when the soils are oven dry and least when they are at 15 bars. I expected the r^2 values for the 1/3 bar to be lower than the 15 bar values because the spectral reflectance at every wavelength measured decreases

Fig. 15 - Coefficients of determination vs. wavelength for organic carbon and spectral reflectance at each moisture level.

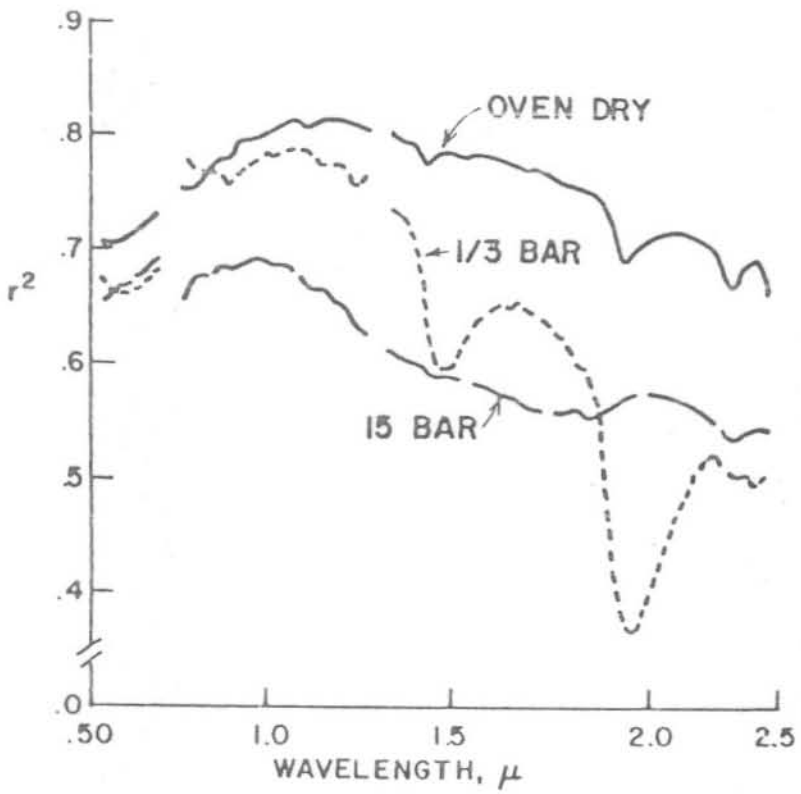


Fig. 15

Table 4. Coefficients of determination for each organic carbon method vs. oven dry spectral reflectance for 10 wavelength bands.

Band Width	Coefficients of Determination (r^2)					
	Allison		Mebius		Walkley-Black	
	.149 mm*	.42 mm	.149 mm	.42 mm	.149 mm	.42 mm
.90- .93	.802	.783	.774	.765	.828	.803
.93- .96	.801	.780	.770	.759	.835	.800
.96-1.00	.807	.786	.778	.763	.843	.805
1.00-1.03	.821	.798	.791	.776	.853	.819
1.03-1.06	.819	.796	.789	.771	.852	.817
1.06-1.09	.823	.799	.791	.774	.858	.819
1.09-1.12	.823	.798	.794	.777	.861	.821
1.12-1.15	.822	.795	.796	.775	.864	.821
1.15-1.18	.823	.794	.796	.781	.862	.823
1.18-1.22	.827	.799	.799	.787	.863	.827

* Values used in Figure 16.

as the amount of water increases (Fig. 14), therefore having less variation in spectral response to be explained. This is true when only the amount of water present is used to explain the variation in spectral reflectance (Fig. 16), however, this reasoning is supported only in the water absorption bands (1.4 and 1.9 μ m) when using just the organic carbon percentages. This indicates that even though the variation is reduced by increasing amounts of water, organic carbon effectively explains the variation in spectral reflectance of soils at the same moisture level especially from .90-1.22 μ m.

At least 62% of the variation in spectral response (15 bars) can be explained by organic carbon and up to 82% (oven dry) at best, indicating the band from .90-1.22 μm should be the best spectral region to use in field studies to map organic carbon content. This band, in previous field studies, has been split at 1.00 μ m (Table 1), if the entire band (.90-1.22 μ m) had been measured, the results of Horvath et al. (1971), Baumgardner et al. (1970), Al-Abbas et al. (1972), and Baumgardner and Staff (1972) might have had higher percent correct identification of organic matter contents. The spectral curves presented by Mathews (1972) and Bower and Hanks (1965) of soils before and after oxidation of organic carbon with hydrogen peroxide show the widest distance between the spectral response curves before and after treatment at the region .90-1.22 μm (Figs. 9, 10).

Lindberg and Snyder (1972) stated all the reflectance minima (absorption maxima) shown by the reflectance spectra of kaolinite

Fig. 16 - Coefficients of determination vs. wavelength for water and spectral reflectance at each moisture level.

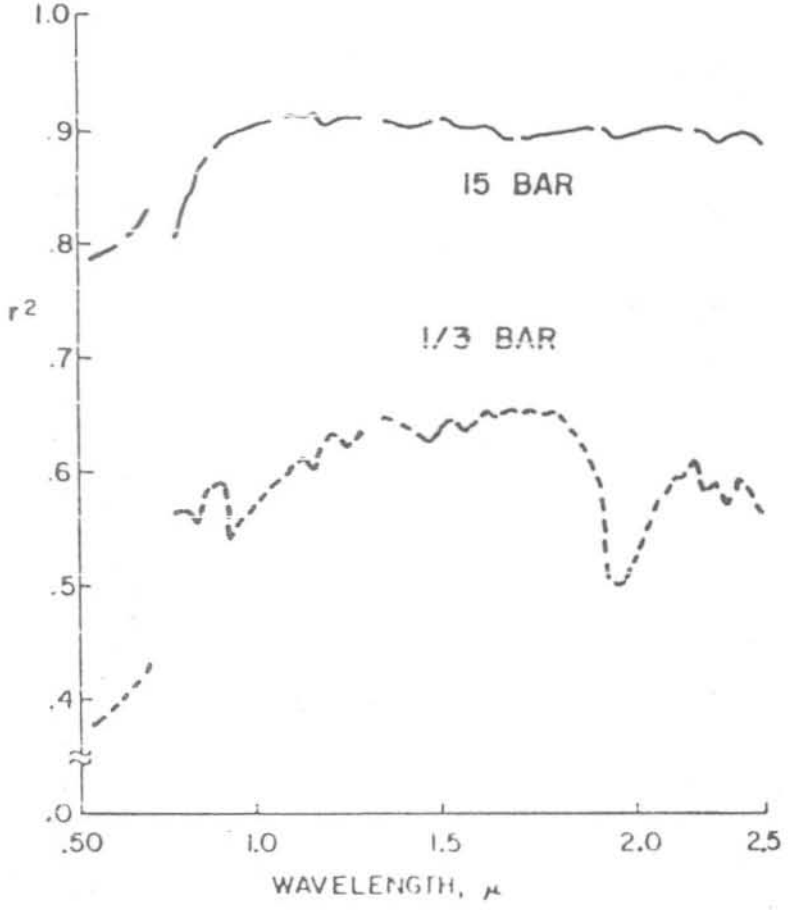


Fig. 16

(Fig. 5) and montmorillonite (Fig. 4) in the near infrared can readily be accounted for by comparison with the reflectance spectra for water (Fig. 12). This statement describes the reflectance spectra of montmorillonite but not kaolinite (Fig. 5) because of its limited absorption of water, notice the lack of absorption at 1.9 μm which must be occur if water is present. The spectral reflectance curve in Figure 14 suggests montmorillonite is the dominant clay in the samples of this study. Figure 16 shows that the absorption band at 1.9 μm for samples at 1/3 bar water explains less of the variation in spectral response than any other region in the infrared. Since all soils in the field are not at the same moisture content due to other factors, this would be a band to avoid in attempting to map surface moisture content of soils. Or possibly it may be of value as a denominator or numerator in using ratios to aid in mapping the surface moisture of soils, because it is difficult to determine if water is present if both the 1.4 and 1.9 μm reflectance values are not used.

Clay and the amount of water held are highly correlated in these samples (.80). In Figure 17 the 1/3 bar r^2 values explain more variation in spectral response than 15 bar or oven dry samples. The low r^2 values are due to little variation in the spectral curves of the samples at 1.9 μm because of the strong absorption of energy leaves little variation to be explained. Whereas Figure 16 gave little indication which region would offer the greatest amount of explanation in the variation of spectral response of the samples, Figure 17 does. Since not all soils in the field would be expected

Fig. 17 - Coefficients of determination vs. wavelength for clay and spectral reflectance at each moisture level.

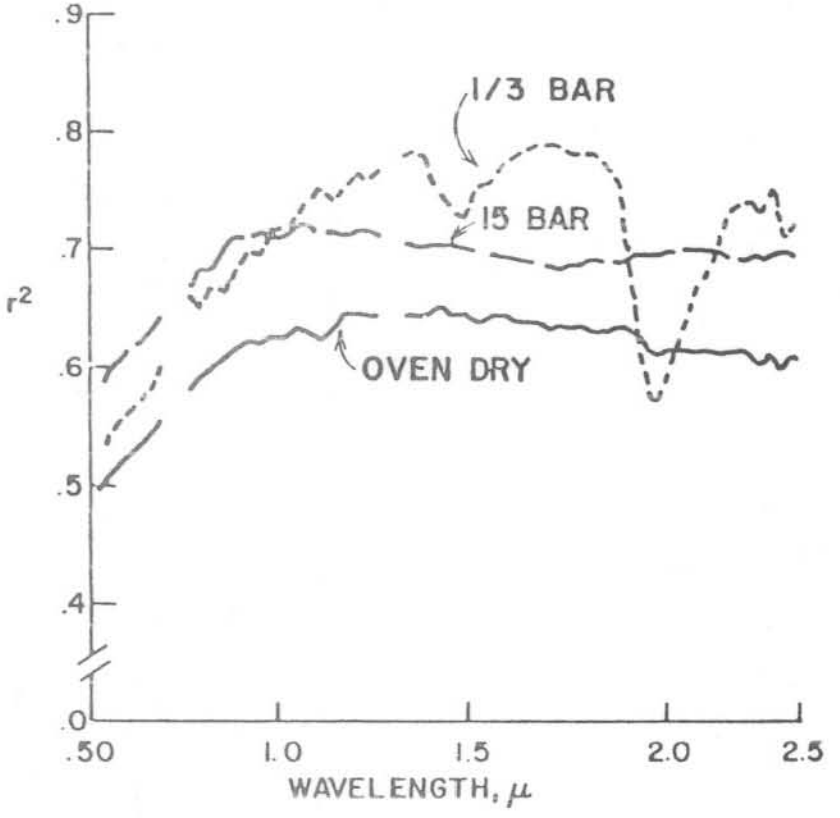


Fig. 17

to be at the same moisture content, the highest r^2 values at all moisture levels would be the region from 1.4-1.9 μm. To say whether clay type or water could be mapped is somewhat insignificant, since for a given clay the amount of water capable of being held is determined by the amount of clay present. For these predominantly montmorillonitic soils, the band from 1.4-1.9 μm would be expected to give the best results in mapping clays or moisture of surface soils as indicated by Lindberg and Snyder (1972) and Bower and Hanks (1965).

Figures 18 and 19 indicate that the other two constituents of texture don't explain much of the variation in the spectral response of these soils. This can be explained by the fact that these soils are predominantly silty and don't have much sand in them and the samples were not selected to obtain a wide range of textures. These findings disagree with Mathews (1972) and Montgomery and Baumgardner (1974), however. I will attempt to explain the difference in Montgomery's findings but can offer no explanation of Mathew's findings since I have no access to his original data.

When examining Montgomery's spectral curves, it becomes evident that not all the samples of the same order have the same type of clay since the shapes of the curves are different. But, looking at the curves that are similar in shape, the amount of organic carbon present in the samples generally explains the overall percent reflectance at any wavelength. If the organic carbon content is high, the entire spectral curve for that sample has the lowest percent reflectance, etc. This is true as long as the percent silt is about the same,

Fig. 18 - Coefficients of determination vs. wavelength for silt and spectral reflectance at each moisture level.

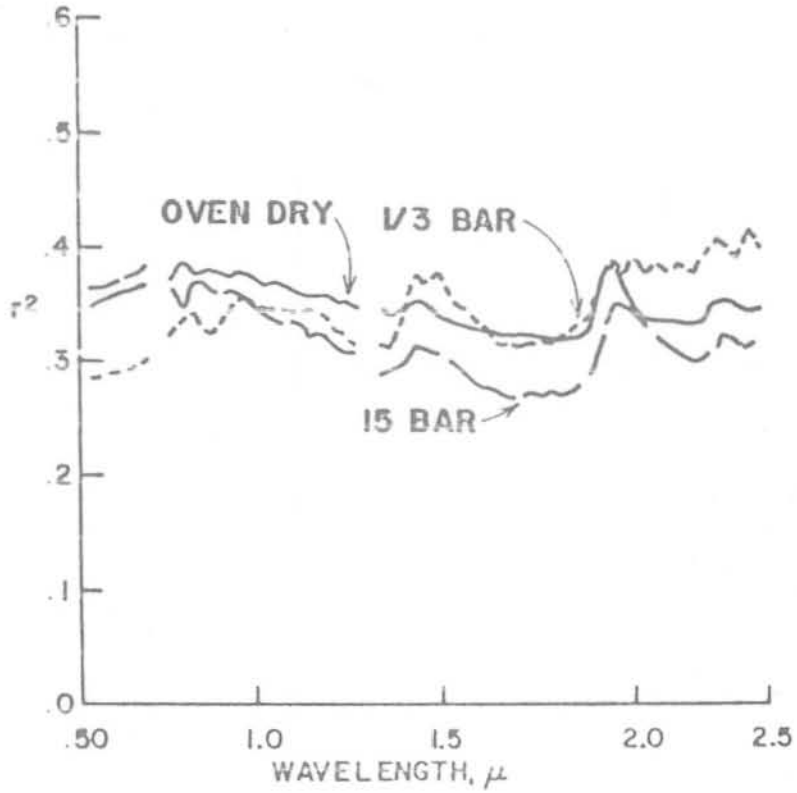


Fig. 18

Fig. 19 - Coefficients of determination vs. wavelength for sand and spectral reflectance at each moisture level.

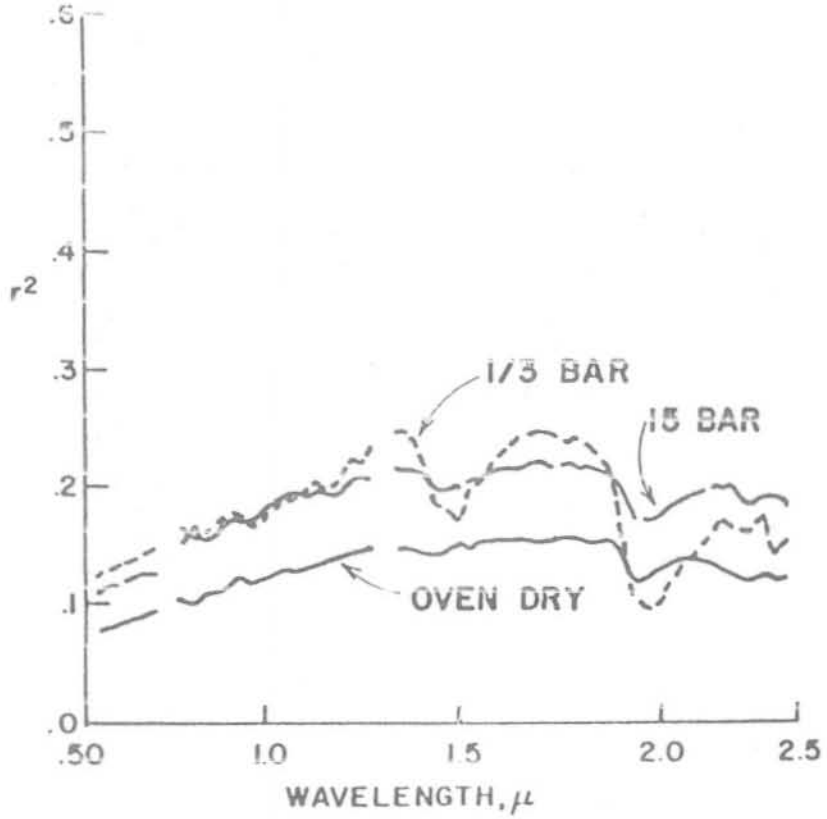


Fig. 19

but if the percent silt varies greatly so does ranking of the spectral curves as Montgomery's work indicates. His data indicates that if two similarly shaped spectral curves of soils have the same organic carbon content, the soil with the greatest amount of silt has the highest reflectance. This may be due to an increase in the amount of surface area and a resulting thinner coat of organic carbon as the amount of sand decreases and silt increases. As the thickness of the organic carbon coating is decreased the amount of spectral energy reflected increases. So when dealing with soils varying more in silt than in organic carbon or clay content, the variation in spectral response can best be explained by the amount of silt.

Figure 20 shows the amount of variation in spectral response that can be explained when all the soil properties measured, except sand, are entered into the multiple regression. Water enters the multiple regression first followed by organic carbon at the 1/3 bar moisture level. Whereas at 15 bars, the organic carbon enters first from .53 to 1.15 μm followed by silt and from 1.31μ m to 2.32 μm clay enters first followed by organic carbon and silt. The regression of oven dry soils which contain no measurable water, organic carbon enters the multiple regression followed by silt and then clay. Sand was not used in the multiple regression because when entered, it caused the singularity of the matrix.

With all the items but sand in the multiple regression (Fig. 21) 77 to 93% of the variation in spectral response was explained indicating the best that could be expected with the properties measured.

Fig. 20 - Multiple coefficients of determination vs. wavelength for organic carbon, silt, clay, water and spectral reflectance at each moisture level.

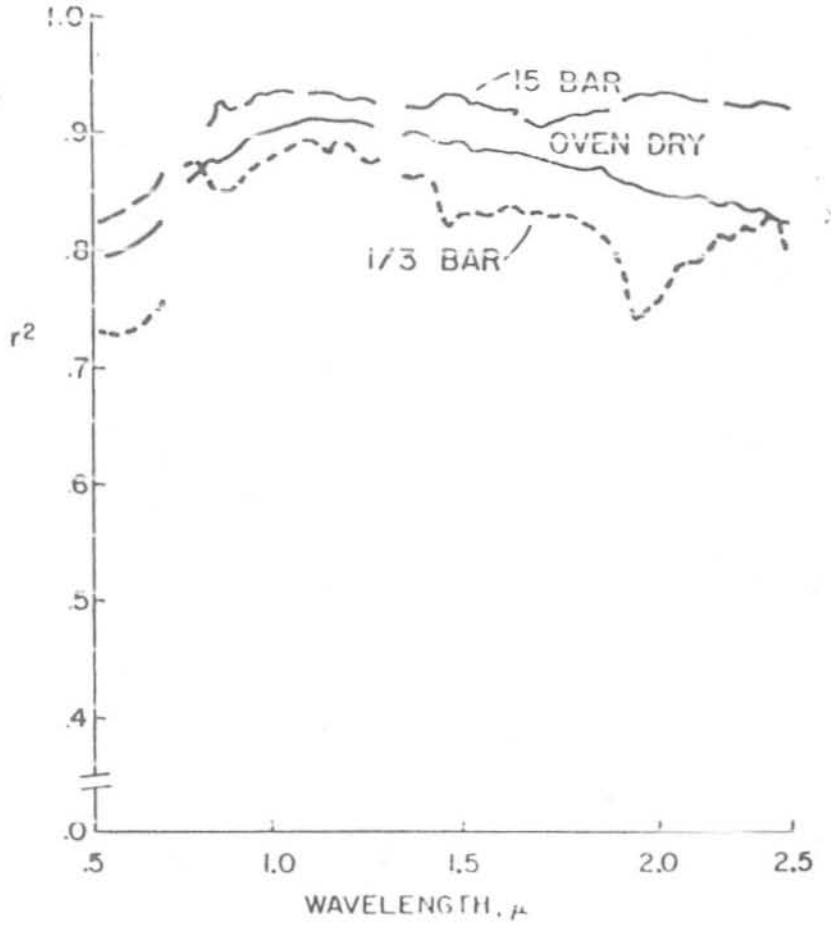


Fig. 20

Fig. 21 - Multiple coefficients of determination vs. wavelength for organic carbon, silt, clay, water and spectral reflectance.

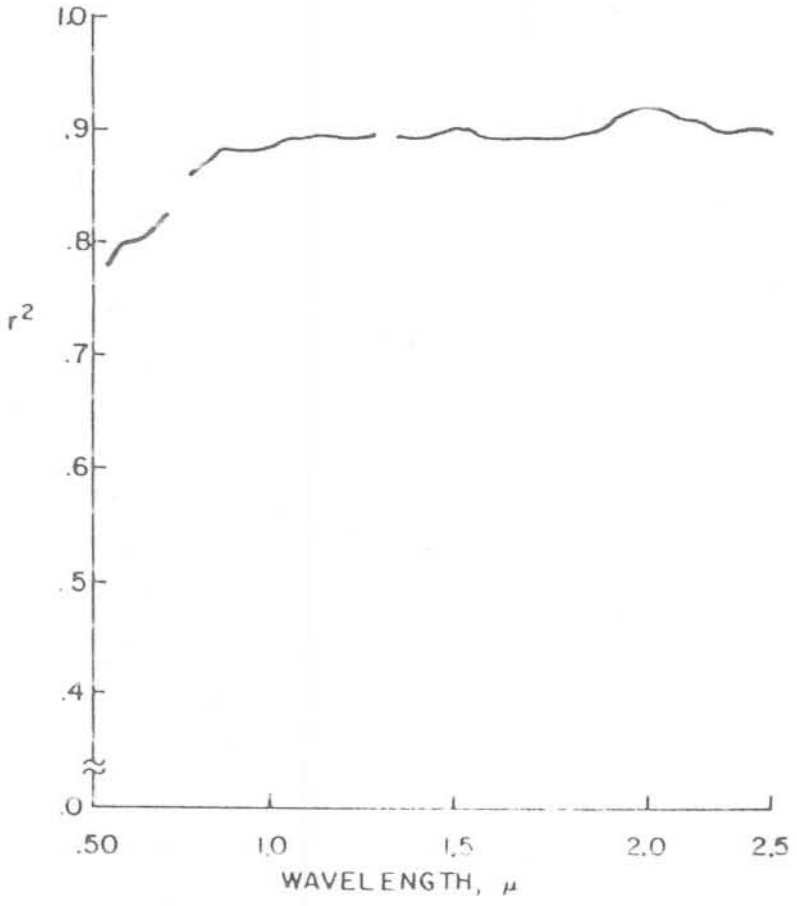


Fig. 21

SUMMARY

By measuring certain physical properties of fifteen soils typical of Wisconsin-aged, glacial till soils capped with less than 60 inches of loess in Indiana, the variations in spectral response in the laboratory were explained. Spectral reflectance measured with the Exotech 20-C can be significantly explained by percent moisture, organic carbon, and clay content of these soils. The soils studied were predominantly silty with a range of organic carbon from .60 to 1.33%. The moisture content of the soils was controlled by use of the pressure membrane at 15 bars, pressure plates at 1/3 bar, and oven dried at 105°C for 24 hours in a forced air dryer. The moisture of the samples was equilibrated, and then illuminated artificially by a General Electric DXW lamp and spectrally measured from .53µm to 2.32 µm with Exotech 20-C.

The interpretation of the results allows me to suggest three wavelength bands widths for use in the field in an attempt to classify surface soils and increase the accuracy in mapping them by multispectral scanner techniques.

1. To map organic carbon use the band from .90 to 1.22 µm.
2. To map water content use the band from 1.50 to 1.73 µm.
3. To map clay use the band from 1.50 to 1.73 µm.

The amount of moisture present affects the spectral response of soils the most followed by organic carbon content, percent silt and then

percent clay with multiple regression analysis.

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